Computers and Electronics in Agriculture 99 (2013) 65–76

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

The design and testing of a small-scale wind turbine fitted to the ventilation fan for a livestock building

S.-W. Hong [a,b], I.-B. Lee [a,*], I.-H. Seo [c], K.-S. Kwon [a]

[a] Department of Rural Systems Engineering and Research Institute for Agriculture and Life Sciences, College of Agricultural and Life Sciences, Seoul National University, 599 Gwanangno Gwanakgu, Seoul 151-742, Republic of Korea
[b] Department of Biosystems, Division M3-BIORES: Measure, Model & Manage Bioresponses, Katholieke Universiteit Leuven, Kasteelpark Arenberg 30, 3001 Heverlee, Belgium
[c] Center for Green Eco Engineering, Institute of Green Bio Science and Technology, Seoul National University, Republic of Korea

ARTICLE INFO

Article history:
Received 11 January 2013
Received in revised form 10 July 2013
Accepted 21 August 2013

Keywords:
Blade element momentum (BEM) method
Energy recovery
Small-scale wind turbine
Ventilation fan

ABSTRACT

Small-scale wind power generation is at present not promising in Korea because of low-speed and unstable natural wind conditions. A wind turbine, which uses artificial and high-speed wind created at the ventilation fan of a livestock building, is proposed as an alternative to conventional approaches. The new blades developed in this study were designed with blade element momentum (BEM) method and optimized on the complex airflow of the ventilation fan. A three-phase alternating current permanent magnet synchronous generator (PMSG), tower, power converter and additional accessories were designed and used to build a wind power system. The wind power system was finally installed on a broiler house and tested by AC load tester. As a result of the evaluation, the new blades of 1.54 m in diameter showed 350 W of electricity output, while the system produced 300 W of electricity because of the electricity loss during the power conversion process. Considering the ventilation fan emits 1 kW of energy, the wind power system recovered 30% of its energy and converted it into usable energy. The load imposed on the existing ventilation system during the generation process, such as loss of ventilation flow rate and increase of electricity consumption, was also investigated. There was only a 1.5% ventilation rate reduction and therefore it can be concluded that there was almost no additional load on the existing ventilation fan operation suggesting economic assistance for those who are suffering from increased energy costs in the livestock farming industry.

1. Introduction

Towards the end of the 20th century, the worldwide environmental and energy crises have led to increased interest in alternative energy sources. The Korean government has exerted great effort to increase energy supply through new and renewable energy sources under the paradigm of “green growth” (KK, 2008). The agricultural industry, which is significantly affected by energy savings and energy efficiency, has also tried to introduce new and clean energy sources into agricultural buildings (RDA, 2008).

New and renewable energy sources, which substitute energy for petroleum, are classified into eight renewable sources, such as solar, biomass, wind, hydropower, and geothermal, and 3 new sources, such as fuel cells. Wind power systems are an alternative energy source technology that converts the kinetic energy of wind into a useful form, such as electricity or heat, using wind turbines. Compared to other energy sources, wind energy has many advantages. Wind energy is clean and comparatively cheap in terms of energy conversion. It also needs less land for generation and can be combined with farming, thus enabling efficient land use (KEMC, 2008). However, the use of wind power generation is very limited in Korea because wind conditions in Korea are comparatively poor and difficult to be predicted (Oh et al., 2012). Only a few areas are judged to be profitable, even for large-scale wind power systems. The usability of wind power is even more limited for small-scale wind power systems because such systems have difficulties in obtaining a high wind speed at the relatively low altitudes where the wind turbines are installed. High wind speed and stable wind conditions are the fundamental requirements for efficient electricity production; the wind energy available for energy conversion is highly dependent on wind speed. Several studies have tried to produce electricity by installing wind power systems on the roofs of high-rise buildings (Park and Kyung, 2003; Choi and Chang, 2009; Ledo et al., 2011); however, the use of natural wind still has limitations by instable and low power production.

In contrast to natural wind, artificial wind, such as that generated by ventilation fans, can be a good alternative to the limitations of natural wind. The wind behind the fan is useless for indoor ventilation, but it is very dense and high-speed and is therefore appropriate for wind power generation. Wind power is proportional to the cube of wind speed. Therefore, if the natural wind speed is 3 m s^{-1} and the artificial wind speed is 10 m s^{-1}, the wind power from the artificial wind is approximately 37 times higher

---

* Corresponding author. Tel.: +82 2 880 4586.
E-mail address: iblee@snu.ac.kr (I.-B. Lee).

0168-1699/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.compag.2013.08.020

than that of the natural wind. In addition, the ventilation fan flow facilitates year-round power generation because ventilation fans for livestock buildings operate year-round to release harmful gases from buildings and to control indoor thermal conditions. Furthermore, it has the advantages of saving on manufacturing costs for unnecessary parts, such as the yaw, pitch controller and gearbox which are used to effectively extract mechanical energy from the variable wind speed and direction, as well as convenient power regulation due to the consistent wind speed and direction generated by the ventilation fan. According to the June 2012 survey by Statistics Korea (KOSIS, 2012), approximately 3700 households work in poultry farming, and, on average, they each hold a few livestock houses. Each house has about one dozen ventilation fans, so, in total, there are tens of thousands of fans that are potential sources for wind power generation. An application to swine farming would give rise to a more than twofold increase of the possible wind power sources. Reutilization of ventilation flows can therefore be an effective plan to reduce the energy burden of livestock farm holders in the context of the global energy crisis.

However, one problem that arises in ventilation fan flow use for wind power generation is the additional pressure load to the ventilation fan. Wind turbines may increase the electricity consumption of the fan or decrease the flow rate through the fan. Hong et al. (2012a,b) investigated the decrease of ventilation fan performance for two different-sized rigid walls. According to their experiments, the large barrier wall, which was four times the size of the ventilation fan, reduced fan performance by 5–21%; the small barrier wall, of the same size as the ventilation fan, reduced fan performance by 2–14% at a distance of 0.5–2 m from the fan. In addition, drag coefficient of flat rigid plate normal to airstream ranges from 1.28 to 1.9 or over 2 due to strong negative pressure at the rear of the plate (Lasher, 2001; Igarashi and Terachi, 2002; Cengel and Turner, 2004), while drag coefficient of a lift-based wind turbine ranges from 0.7 to 1.0 by the formula $C_D \approx 7/V_{\text{hub}}$ (Frohboese and Schmuck, 2010) when the wind speed at the height of wind turbine hub is assumed 7–10 m s^{-1}. Therefore the drag coefficient for lift-based wind turbines is simply estimated to be 37–78% that of a rigid wall because of its air penetrability. In general, a lift-based wind turbine receives low drag force and axial thrust force from the wind compared to drag-based wind turbines, and it is therefore expected to exert a low reverse load on the ventilation fan for wind power generation.

One of the major factors for the efficient reutilization of the ventilation fan flow may be the proper design of the blades of the wind turbine. The ventilation fan flow has very complex eddies and vortexes, and its velocity varies along the radial direction. In the long view, a constantly rotating fan produces a well-regulated flow pattern that shows a formulated radial distribution of velocity. Unlike natural wind, which has a uniform velocity distribution, new designs for the wind turbine and its blades are required for ventilation fan flow.

In this study, a small-scale wind power system was developed to produce electricity by reutilizing the ventilation flow of a 50-in. fan, a size typically used in livestock buildings in Korea. The new blades of the wind turbine were designed to be properly adapted to complex wind flows generated by the ventilation fan. The wind power system was evaluated and tested in a field application.

2. Materials and methods

To develop a wind power system for the rear side of ventilation fans, this study took the following four steps: step 1 – analyze airflow at the rear side of the ventilation fan, step 2 – design wind turbine blades based on the characteristics of the airflow at the rear side of the ventilation fan, step 3 – evaluate the efficiency of the wind turbine and the generator through lab experiments, and step 4 – install the wind power system, including a power-converting system, on an actual broiler house to evaluate the system.

The first step was conducted by Hong et al. (2012a), and it is briefly cited in the results and discussion. In this study, the researcher undertook the blade design, wind power system installation, and the evaluation of the system, which are the most important elements of wind power design.

2.1. Physical descriptions of the blade design

2.1.1. A Brief Description of blade element momentum method

Blade element momentum (BEM) method combines momentum theory and blade element theory (Griffiths, 1977; Burton et al., 2001; Lanzafame and Messina, 2009). It is the most widely used classical theory, both to interpret the dynamics of rotor blades and to design a blade section. Momentum theory describes the relationship between the power upon rotors and the fluid velocity generated by the power. Using momentum theory, one can estimate rotor efficiency. However, momentum theory does not stipulate how to design rotor blades. Blade element theory divides the blades into several elements and calculates the power that affects each blade element in terms of fluid velocity. The power upon the blade element relies on the lift force (F_L), drag force (F_D), fluid velocity (V_r) and direction (α). These relationships are described in Fig. 1.

The wind at the back and front side of the rotor is simplified and described as axial and tangential induction factors “a” and “a_T”, defined as the following (Burton et al., 2001):

$$V_r = V_1(1-a) \tag{1}$$

$$W_r = \Omega r(1+a_T) \tag{2}$$

where V_r and W_r are the axial and tangential velocity components, respectively, in the rotor plane, V_1 is the incoming free stream velocity, Ω is the angular velocity of the rotor, r is the radius of the rotor, and a and a_T are the axial and tangential induction factors, respectively.

The power upon the rotor blades and wind changes between the back and front side of the rotor are described as induction factors “a” and “a_T”, and the torque of the rotor blades is calculated by estimating the induction factors “a” and “a_T”. By using 1/3 of the theoretical “a” value, which shows the optimal performance, the optimal design of the rotor blade can be designed (Burton et al., 2001; Hau, 2005). This theory, however, is based on an assumption that there are enough blades to absorb the momentum from the fluid. In reality, a small number of blades are used, and much of the fluid flows in between the blades and is not necessarily forced on the rotor. Furthermore, the flow passing through the blades creates complex three-dimensional secondary flows and affects the performance of the next blade. Due to this, there is a decrease in momentum compared to the ideal condition. The decrease is described by Prandtl’s loss factor “f”, and its application is available by multiplying induction factors “a” and “a_T” (Burton et al., 2001; Martinez et al., 2005).

$$f(\mu) = \frac{2}{\pi}\cos^{-1}\left\{\exp\left[-\frac{N}{2}\left(\frac{1-\mu}{\mu}\right)\sqrt{1+\left(\frac{\lambda\mu}{1-a}\right)^2}\right]\right\} \tag{3}$$

where f is the Prandtl’s loss factor, $\mu(=r/R)$ is the radial blade coordinate (r) normalized with respect to the blade radius (R), N is the number of blades, and λ is the tip speed ratio (TSR) ($=R\Omega/V_1$).

This factor equals 1 for most positions of the blade, but goes to 0 at the blade tip and the blade root. Applying Prandtl’s loss factor to BEM method, two formulas regarding “a” and “a_T” are generated as